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The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

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RPPR Final Report
as of 15-Feb-2018

Agency Code:

Proposal Number: 69262EGCF **Agreement Number: W911NF-16-1-0476**
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Report Date: 12-Dec-2017 Date Received: 28-Dec-2017
Final Report for Period Beginning 13-Sep-2016 and Ending 12-Sep-2017
Title: Workshop on "Robotics Materials"
Begin Performance Period: 13-Sep-2016 **End Performance Period:** 12-Sep-2017
Report Term: 0-Other
Submitted By: Ph.D Nicolaus Correll Email: ncorrell@colorado.edu
Phone: (303) 492-2233
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 4 **STEM Participants:** 1

Major Goals: Bringing together leading scientists in the field of sensor networks, robotics and material science to discuss the fundamental challenges in creating "robotic materials" that tightly integrate sensing, actuation, computation, and communication.

Accomplishments: The PI brought together 35 scientists in Boulder, CO for a two-day workshop. After brief introductions, participants were organized in groups to brainstorm both applications and specific challenges of robotic materials, including their potential for distributed sensing, actuation, and communication. Results from the workshop were synthesized into two position papers "New Directions: Wireless Robotic Materials" and "Materials that make robots smart", with the key insight that robotic materials should leverage silicon-based wireless networking technology to provide computation and are optimally powered wirelessly.

Training Opportunities: Multiple PhD students and one undergraduate student also participated in the sessions.

Results Dissemination: Results from the workshop have been disseminated at a premier sensor network and robotics conferences.

Honors and Awards: 1st price ("Best Paper") at the International Symposium on Robotics Research for the paper "Materials that Make Robots Smart" from 18 submissions to the "Blue Sky" visioning track.

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Nikolaus Correll
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

RPPR Final Report
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CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation **Publication Status:** 0-Other
Conference Name: International Symposium on Robotics Research
Date Received: 28-Dec-2017 Conference Date: 08-Dec-2017 Date Published:
Conference Location: Puerto Varras, Chile
Paper Title: Materials that Make Robots Smart
Authors: Nikolaus Correll, Christoffer Heckman
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 0-Other
Conference Name: ACM Conference on Embedded Networked Sensor Systems (SenSys)
Date Received: 28-Dec-2017 Conference Date: 07-May-2017 Date Published:
Conference Location: Delft, The Netherlands
Paper Title: New Directions: Wireless Robotic Materials
Authors: Nikolaus Correll, Prabal Dutta, Richard Han, Kristofer Pister
Acknowledged Federal Support: **Y**

WEBSITES:

URL: http://wrm2017.wordpress.com
Date Received: 28-Dec-2017
Title: Workshop on Robotic Materials
Description: Workshop website containing links to all materials created by participants (google slides)

Workshop on Robotic Materials

Final Progress Report

List of Appendixes

List of Participants

Problem Statement

Creating "robotic materials" that mimic the tight integration of sensing, actuation, computation and communication that is common in biological tissue requires interdisciplinary collaboration between previously disjoint fields. This workshop has explored what it would take to create such materials by inviting researchers that represent the fields of sensor networks, robotics, and material science together with leading biologists who study representative model systems such as tactile sensation in the human skin or the neural system of the octopus.

Summary of the most important results

There was broad agreement that miniaturization of **computation**, availability of a large variety of phase-changing polymers, and novel manufacturing techniques has made the creation of robotic materials a timely and important endeavor. To implement computation, **silicon is preferable** over other emerging techniques (polymer electronics, e.g.) due to the small size, the high speed, and the low cost of this approach. Polymer electronics, however, is preferable whenever larger areas (in the order of centimeters) need to be covered with sensors or actuators, and when the required computation is very simple including preprocessing and simple control. There was also consensus that any additional wiring that needs to be introduced into a composite material comes with numerous challenges including increased complexity of manufacturing and decreased structural integrity. Specifically, wires require accurate placement of sensors and computers and cumbersome placement of interconnects.

With the availability of high-performance, low cost, low energy wireless networking, it is likely that **communication in any practical robotic material will be wireless**. Following a similar reasoning, **sensing, computation, and actuation would be powered wirelessly** in an ideal robotic material. Which components will be communicating and be powered wirelessly will be application and technology dependent, with wirelessly powered robotic materials that sense, compute, and communicate wirelessly being feasible in the near future. Here, the keynote speakers inspired obvious applications in tactile sensing and camouflage skins.

The research challenges of robotic materials are on **phase-changing polymers for sensing and actuation**, the **algorithms that coordinate large number of distributed computing elements**, and the **applications of robotic materials** across the spectrum of engineering disciplines from aerospace to mechanical and civil engineering. All of these sub-fields have already made tremendous progress in recent years, shifting the key challenge on the **integration of sensors, actuators, and computers into materials that harvest, store, and metabolize energy**, suggesting a new "**science of material integration**".

The workshop had overlap with the Army's science strategy planning workshop in December 2016 and led to numerous follow-up events, including a workshop on "Material

Robotics" co-organized by Correll and one of the participants (Rebecca Kramer, Yale) and a pending workshop sponsored by CRA/CCC in Washington, DC, in Spring 2018. **Results from the workshop have been disseminated in two publications**, a position paper at the premier sensor networking conference ACM SenSys "New Directions: Wireless Robotic Materials" by N. Correll, P. Dutta, R. Han and K. Pister [1] and "Materials that Make Robots Smart" by N. Correll and C. Heckman [2], at a premier robotics conference (ISRR), where it was awarded with the 1st place at the CCC-sponsored "Blue Sky" track as the most visionary paper. Finally, the workshop and its result was critical in making "Multi-functional Materials" one of six focus areas of the college of engineering and applied sciences at the University Colorado for the next four years, an effort led by PI Correll.

Bibliography

[1] R. Han, N. Correll, K. Pister, P. Dutta. New Directions: Wireless Robotic Materials. 15th ACM Conference on Embedded Networked Sensor Systems (SenSys), Delft, The Netherlands, 2017.

[2] N. Correll, C. Heckman. Materials that Make Robots Smart. International Symposium on Robotics Research (ISRR), Puerto Varas, Chile, 2017.

Appendix: List of Participants

Zhenan Bao, Stanford University
Ray Baughman, University of Texas at Dallas
Fu-Kuo Chang, Stanford University
Nikolaus Correll, University of Colorado at Boulder
Mark Cutkosky, Stanford University
Prabal Dutta, University of California Berkeley
Ron Fearing, University of California Berkeley
Mark Gross, University of Colorado at Boulder
Rick Han, University of Colorado at Boulder
Christoffer Heckman, University of Colorado at Boulder
Benny Hochner, Hebrew University of Jerusalem (see Keynotes)
Sean Humbert, University of Colorado at Boulder
Roland Johansson, Umeå University (see Keynotes)
Christoph Keplinger, University of Colorado at Boulder
Rebecca Kramer, Purdue / Yale University
Dirk Lehmhus, ISIS Sensorial Materials Scientific Centre, University of Bremen
Byung-Lip "Les" Lee, Airforce Office of Scientific Research
Carmel Majidi, Carnegie Mellon University
Kurt Maute, University of Colorado at Boulder
Thomas McKenna, Office of Naval Research
Michael Peshkin, Northwestern University
Kirstin Petersen, Cornell University
Ron Pelrine, Stanford Research Institute
Kris Pister, University of California Berkeley

Jacob Segil, University of Colorado at Boulder
Sean Shaheen, University of Colorado at Boulder
Robert Shepherd, Cornell University
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Geoffrey Slipher, US Army Research Laboratory
Michael Tolley, University of California San Diego
Richard Voyles, Purdue University
Shawn Walsh, US Army Research Laboratory
Richard Weir, University of Colorado Anschutz Medical Campus
George Whitesides, Harvard University
Jianliang Xiao, University of Colorado at Boulder